

A FINITE-ELEMENT MODEL FOR EVALUATION OF MIDDLE EAR MECHANICS

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Abstract- A computer model of the middle ear, ossicular chain and eardrum was established using the finite-element method. A preliminary comparison of the model with measurements made in human-cadaver ears shows that the model is in approximate agreement with the form of the middle ear function. The computer model will be used for implant design.

Keywords- Ossicular chain, finite element modeling, middle ear

I. INTRODUCTION

Defects of the incus occur in 59% of conductive hearing loss cases [1]. For efficient restoration of hearing the defective incus is normally removed and the mechanical link between the eardrum and inner ear is reconstructed. The method used to reconstruct this ossicular chain depends on the nature of the defect and the remaining healthy anatomy of the ear.

In cases of incus defects the reconstruction is normally of the form of a rod, positioned to connect the malleus handle or eardrum directly to the cochlea oval window. This arrangement does not take advantage of the mechanical lever offered by the intact chain. A more promising approach to prosthesis design is to reconstruct the chain along more physiologically relevant lines. Mills reported clinical success with a physiological reconstruction, connecting the stapes head to the malleus head [2, 3]. The authors have previously shown that excellent reconstruction of the ossicular chain can be achieved using a generic incus shape [4]. In a series of *in vitro* studies it was shown that secure attachment of the prosthesis to the stapes and malleus, with ionomer cement, could restore hearing within 10 dB of the original frequency response. This study attempts to model

these *in vitro* findings using a finite element computer model. The goal of the study is to produce a computer model that can be used to simulate different forms of attachment to the prosthesis.

II. METHODOLOGY

The geometry of the model was derived from high-resolution magnetic resonance micro-imaging of human cadaver middle-ear structures [5]. The ossicular chain was immersed in a silicon-oil and the oil imaged to produce volume outlines of the bones. Edge detection was used to trace the outlines and the model constructed using a bottom-up hierarchy from points to volumes [6]. The element mesh was automatically generated and the finite-element program ANSYS5.6 was used for analyzing the model. The model discretization is shown in Fig. 1.

The material properties used to construct the model are shown in Table 1. Material properties are taken from those of Beer *et al.* and Bornitz *et al.* [8, 9]. The human eardrum model was generated using a scheme similar to that of Funnell [7] who defined the curvature of the eardrum using a normalization factor. In this model the normalized radius of curvature=1.28 and the eardrum is anisotropic. The eardrum thickness is assumed to be uniform over its area ($=68 \text{ mm}^2$).

Four-noded triangular shell and tetrahedral solid elements were used to define the eardrum and ossicles respectively. These elements are well suited to modeling irregular geometry, such as that which results from the scanning process.

The eardrum was clamped at the annulus and the stapes footplate restricted to move along the line normal to its surface.

TABLE I
MATERIAL PROPERTIES^a

	Pars Tensa	Pars Flaccida	Ossicles
Young's modulus, E_r (MPa)	85.7×10^6	45.6×10^6	2×10^4
Young's modulus, E_t (MPa)	48×10^6	20×10^6	
Density (kg/m ³)	1200	1200	3300
Shell thickness (m)	100×10^{-6}	100×10^{-6}	n/a
Poisson's ratio	0.35	0.43	0.3
Shear modulus	6.2×10^6	8.5×10^6	n/a
RMI factor ^b	0.78	0.29	n/a

^aValues were taken from [8, 9]

^bBending moment of inertia ratio

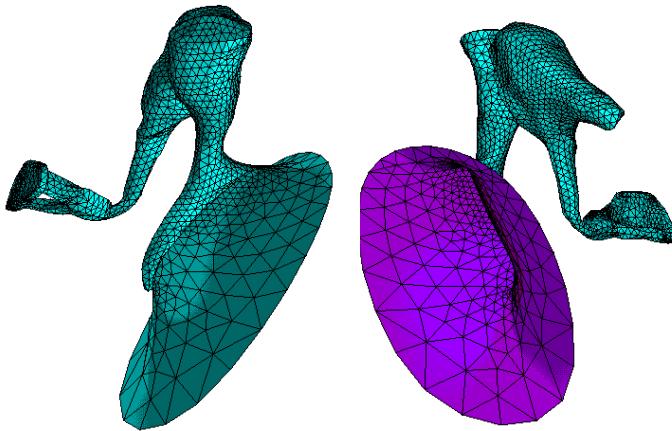


Fig. 1. Two views of the finite-element discretization of the middle-ear.
The eardrum, malleus, incus and stapes are shown.

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The incus was constrained at its short process and the malleus constrained at the anterior process. A pressure load equivalent to 80 dB sound pressure level (SPL) was uniformly applied across the surface of the eardrum. The cochlear load was not modeled.

III. RESULTS

A. Displacement Shapes

Figs. 2 and 3 show displacement contours within the model at forcing frequencies of 1 kHz and 9.5 kHz. Colors show regions of the structure that have the same amplitude of displacement. These plots represent the displacement response at particular forcing frequencies and are not necessarily mode shapes of the middle ear model. Images were generated between 100 Hz and 10 kHz. At low frequency the eardrum vibrates in discrete sections, similar to the concentrated displacements of Fig. 2. In the middle range of frequency the eardrum displacements are generally larger across the whole surface and the vibrating areas are more dispersed. At high frequency there are no concentrated areas of eardrum displacement and this may correspond to a loss of efficiency in transmitting sound, Fig. 3. There is good agreement between these plots and experimental patterns observed in cat [10] and human [11] middle ears.

B. Frequency Response

Fig. 4 shows the frequency response of two points within the finite element (FE) model. One of the points is on the base of the stapes footplate. The other is on the eardrum. The third curve in Fig. 4 is the average frequency response measured in five temporal bone samples to a sound stimulus of 80 dB SPL. The vertical axis shows peak-to-peak displacement normalized to the input sound pressure at the eardrum.

Although the frequency response function varies across the eardrum surface, a single point lying midway between the tip of the malleus and the annulus has been chosen to represent eardrum motion. Below 1 kHz the eardrum and stapes

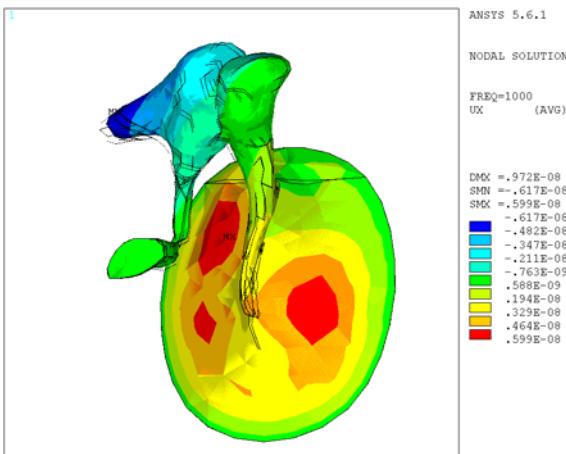


Fig. 2. Displacement plot at 1 kHz, stimulated by 80 dB SPL.

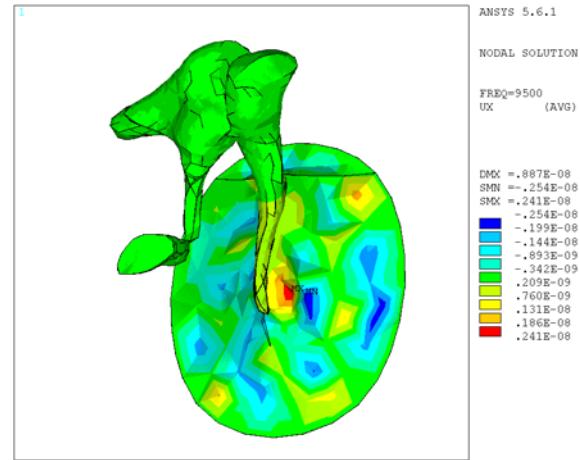


Fig. 3. Displacement plot at 9.5 kHz, stimulated by 80 dB SPL.

responses are reasonably flat, similar to that measured in the temporal bone study. With this set of material properties, the simulated stapes response is considerably less than the response measured in actual ears. At about 1.5 kHz, the response exhibits a resonance that is similar to the first resonance measured in temporal bones. Above this peak the response decreases with frequency. A second resonance occurs at about 4 kHz, again at a higher frequency than measured in temporal bones.

IV. DISCUSSION

Although this is just a preliminary model the form of the middle ear function is in approximate agreement with that found in middle ear studies in temporal bones. Differences are thought to be due to the modeling parameters used. This middle ear model did not consider inhomogeneity in the thickness of the eardrum, nor was the flexible annulus modeled. A better fit of the simulation to experimental data may be achieved by incorporating ligamentous attachments and the cochlear load.

Eardrum displacement is found to be higher than stapes displacement, as expected. The simulated stapes response matches the eardrum response quite well to up to high frequency where the responses differ. This difference represents poor a loss of efficiency of the eardrum driving the malleus.

V. CONCLUSION

The model described here can be further used to predict changes that may occur through modification of the middle ear structures. The main parameters that may be investigated are mass, shape, stiffness and position of the implant. With a better understanding of the effects of these parameters on sound transmission, implant designs could be optimized to produce transmission characteristics that are seen in the normal human ear.

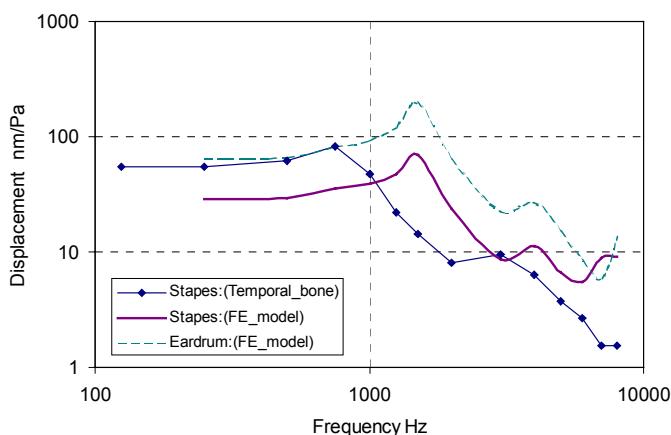


Fig 4. Frequency response of the stapes footplate and eardrum in the finite element model. The average stapes footplate displacement measured in five temporal bone samples is shown for comparison. Stimulation level was 80 dB SPL. The displacement is normalized by the input sound pressure at the eardrum.

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